A quantitative geochemical target for modeling the formation of the Earth and Moon

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The past decade has been one of geochemical, isotopic, and computational advances that are bringing the laboratory measurements and computational modeling neighborhoods of the Earth-Moon community to ever closer proximity. We are now however in the position to become even better neighbors: modelers can generate testable hypthotheses for geochemists; and geochemists can provide quantitive targets for modelers. Here we present a robust example of the latter based on Cl isotope measurements of mare basalts.

Boyce et al. (2015 *Sci. Adv.*) implicated the urKREEP—the highly fractionated last dregs of the lunar magma ocean—as being responsible for the elevated $^{37}Cl/^{35}Cl$ in mare basalts, based on correlations between $\delta^{37}Cl$ and Th or La/Lu. Expanding on the analysis of Boyce et al., we use 8 elements as proxies for KREEPiness. We test the hypothesis that urKREEP is the source of elevated $\delta^{37}Cl$ and is enriched in Cl, consistent with the incompatible nature of Cl. Assuming two component mixing between the urKREEP and mare basalt source, KREEPy elements serve as proxies for Cl in a traditional isotopic mixing model. We can therefore solve for the isotopic composition of the reservoirs ($\delta^{37}Cl_{mare}$ and $\delta^{37}Cl_{urKREEP}$) as well as the relative (but not absolute) enrichment in Cl of the urKREEP over the mare basalt, $[Cl_{mare}/Cl_{urKREEP}]$ by forward modeling. We find that all KREEPy proxy elements are well fit by a single set of model values, indicating that the hypothesis is consistent with the data. $\delta^{37}Cl_{urKREEP}$ = +25‰ (SMOC), whereas $\delta^{37}Cl_{mare}$ clearly defines a distinct reservoir, albeit less well constrained at ~0‰. The Cl abundance of the urKREEP is enriched over the mare basalt by a factor of 50. If uncontaminated mare basalt has ~2 ppm Cl (Hauri et al. 2011 *Science*), then the urKREEP (at 100 ppm) is depleted in Cl relative to CI chondrite by a factor of 7, and relative to refractory Th or U in urKREEP by a factor of 5000 (Warren & Wasson, 1978 *RGSP*).

We demonstrate the existence of—as well as the chemical and isotopic characteristics of—two distinct Cl reservoirs in the lunar interior: the urKREEP and mare basalt source. In addition to many physical, chemical, and isotopic prior constraints, the urKREEP now has a Cl concentration, $\delta^{37}Cl$, and chlorine isotopic fractionation factor, permitting it to serve as a highly useful quantitiative target for modelling efforts aimed at building the Moon.